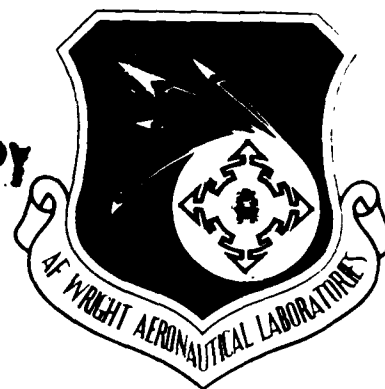


AD-A193 420

2

AFWAL-TR-88-4081

DTIC FILE COPY



CONSTANT AMPLITUDE FATIGUE LIFE DATA FOR NOTCHED AND
UNNOTCHED ANNEALED Ti-6Al-4V SHEET

Torsten M. Rhode, Capt, USAF
Systems Acquisition and
Logistics Support Branch
Systems Support Division

Patrick W. Ertel
University of Dayton
Research Institute
300 College Park Avenue
Dayton, OH 45469



January 1988

Final Technical Report for Period January 1983-September 1986

Approved for Public Release; Distribution Unlimited.

MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533

88 5 17 084

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Torsten M. Rhode

TORSTEN M. RHODE, Capt, USAF
Project Engineer
Materials Engineering Branch

Clayton L. Harmsworth

CLAYTON L. HARMSWORTH
Technical Manager for
Engineering & Design Data
Materials Engineering Branch

FOR THE COMMANDER

Theodore J. Reinhart

THEODORE J. REINHART, Chief
Materials Engineering Branch
Systems Support Division
Materials Laboratory

If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization, please notify MLSE, WPAFB, OH 45433-6533 to help us maintain a current mailing list.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

| REPORT DOCUMENTATION PAGE | | | | Form Approved OMB No. 0704-0188 | |
|--|-------|--|---|------------------------------------|----------------------------------|
| 1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED | | | 1b. RESTRICTIVE MARKINGS | | |
| 2a. SECURITY CLASSIFICATION AUTHORITY | | | 3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release; Distribution Unlimited | | |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | | | | | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFWAL-TR-88-4081 | | | 5. MONITORING ORGANIZATION REPORT NUMBER(S) | | |
| 6a. NAME OF PERFORMING ORGANIZATION Systems Support Division Materials Laboratory | | 6b. OFFICE SYMBOL (if applicable) AFWAL/MLSE | 7a. NAME OF MONITORING ORGANIZATION | | |
| 6c. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB, OH 45433-6533 | | | 7b. ADDRESS (City, State, and ZIP Code) | | |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION | | 8b. OFFICE SYMBOL (if applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER | | |
| 8c. ADDRESS (City, State, and ZIP Code) | | | 10. SOURCE OF FUNDING NUMBERS | | |
| PROGRAM ELEMENT NO. 62102F | | PROJECT NO. 2418 | TASK NO. 07 | WORK UNIT ACCESSION NO. 03 | |
| 11. TITLE (Include Security Classification) CONSTANT AMPLITUDE FATIGUE LIFE DATA FOR NOTCHED AND UNNOTCHED ANNEALED Ti-6Al-4V SHEET. | | | | | |
| 12. PERSONAL AUTHOR(S) Torsten M. Rhode, CAPT, USAF; Patrick W. Ertel, University of Dayton Research Institute | | | | | |
| 13a. TYPE OF REPORT Final Technical Report | | 13b. TIME COVERED FROM 1/83 TO 9/86 | 14. DATE OF REPORT (Year, Month, Day) January 1988 | | 15. PAGE COUNT 41 |
| 16. SUPPLEMENTARY NOTATION | | | | | |
| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) | | |
| FIELD | GROUP | SUB-GROUP | Titanium Alloy, Constant Amplitude Fatigue, Fatigue Life | | |
| | | | Ti-6Al-4V Sheet MIL-HDBK-5 | | |
| 19. ABSTRACT (Continue on reverse if necessary and identify by block number) Three lots of annealed Ti-6Al-4v sheet material in thicknesses of 0.063 inch, 0.070 inch, and 0.078 inch, supplied by two manufacturers, were tested to develop fatigue life curves for MIL-HDBK-5. Notched ($K_t=3.0$) and unnotched configurations of longitudinal and transverse specimens were tested at R-ratios of +0.5, +0.1, and -0.5. Fatigue life data are presented in both tabular and graphical forms. Results were forwarded to the Battelle Memorial Institute, Columbus, Ohio, for analysis, reduction, and inclusion in MIL-HDBK-5. | | | | | |
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS | | | 21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED | | |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL Capt Torsten Rhode / Mr Clay Harmsworth | | | 22b. TELEPHONE (Include Area Code) (513)255-5128 | | 22c. OFFICE SYMBOL AFWAL/MLSE |

DD Form 1473, JUN 86

Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

PREFACE

This report was prepared by the Materials Engineering Branch (AFWAL/MLSE), Systems Support Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. The work was conducted under Project 2418, "Aerospace Structural Materials," Task 07, "Systems Support," Work Unit 03, "Engineering and Design Data."

Testing was performed from January 1983-September 1986; the report was submitted by the authors in August 1987.

| | |
|--------------------|--|
| Approved For | |
| NHS - CRAM | <input checked="checked" type="checkbox"/> |
| OTL - TAB | <input type="checkbox"/> |
| Unpublished | <input type="checkbox"/> |
| Justification | |
| By | |
| Distribution | |
| Availability Codes | |
| Dist | Avail and/or Special |
| A-1 | |



TABLE OF CONTENTS

| <u>SECTION</u> | | <u>PAGE</u> |
|----------------|-------------------------|-------------|
| I | INTRODUCTION | 1 |
| II | MATERIALS AND SPECIMENS | 2 |
| III | PROCEDURES | 4 |
| IV | RESULTS AND DISCUSSION | 5 |
| V | CONCLUSIONS | 6 |

LIST OF ILLUSTRATIONS

| <u>FIGURE</u> | | <u>PAGE</u> |
|---------------|--|-------------|
| 1 | Notched Specimen Geometry | 8 |
| 2 | Unnotched Specimen Geometry | 9 |
| 3 | S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-ratio = +0.5 | 19 |
| 4 | S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-ratio = +0.1 | 20 |
| 5 | S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-ratio = -0.5 | 21 |
| 6 | S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-ratio = +0.5 | 22 |
| 7 | S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-ratio = +0.1 | 23 |
| 8 | S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-ratio = -0.5 | 24 |
| 9 | S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-ratio = +0.5 | 25 |

| <u>FIGURE</u> | | <u>PAGE</u> |
|---------------|--|-------------|
| 10 | S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-ratio = +0.1 | 26 |
| 11 | S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation R-ratio = -0.5 | 27 |
| 12 | S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-ratio = +0.5 | 28 |
| 13 | S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-ratio = +0.1 | 29 |
| 14 | S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-ratio = -0.5 | 30 |

LIST OF TABLES

| <u>TABLE</u> | | <u>PAGE</u> |
|--------------|---|-------------|
| 1 | Chemical Composition of Ti-6Al-4V Sheet Data Supplied by Manufacturers. | 7 |
| 2 | Tensile Data of Annealed Ti-6Al-4V Sheet Data Supplied by Manufacturers. | 7 |
| 3 | Test Matrix. | 10 |
| 4 | Raw Room-Temperature Fatigue Life Data for Longitudinal Unnotched Annealed Ti-6Al-4V Sheet, R-ratio = +0.5. | 11 |
| 5 | Raw Room-Temperature Fatigue Life Data for Longitudinal Unnotched Annealed Ti-6Al-4V Sheet, R-Ratio = +0.1 | 12 |
| 6 | Raw Room-Temperature Fatigue Life Data for Longitudinal Unnotched Annealed Ti-6Al-4V Sheet, R-Ratio = -0.5. | 13 |
| 7 | Raw Room-Temperature Fatigue Life Data for Transverse Unnotched Annealed Ti-6Al-4V Sheet, R-Ratio = +0.5. | 13 |
| 8 | Raw Room-Temperature Fatigue Life Data for Transverse Unnotched Annealed Ti-6Al-4V Sheet, R-Ratio = +0.1. | 14 |
| 9 | Raw Room-Temperature Fatigue Life Data for Transverse Unnotched Annealed Ti-6Al-4V Sheet, R-ratio = -0.5. | 14 |

| <u>TABLE</u> | | <u>PAGE</u> |
|--------------|---|-------------|
| 10 | Raw Room-Temperature Fatigue Life Data for Longitudinal Notched Annealed Ti-6Al-4V Sheet, R-ratio = +0.5. | 15 |
| 11 | Raw Room-Temperature Fatigue Life Data for Longitudinal Notched Annealed Ti-6Al-4V Sheet, R-ratio = +0.1. | 16 |
| 12 | Raw Room-Temperature Fatigue Life Data for Longitudinal Notched Annealed Ti-6Al-4V Sheet, R-ratio = -0.5. | 17 |
| 13 | Raw Room-Temperature Fatigue Life Data for Transverse Notched Annealed Ti-6Al-4V Sheet, R-ratio = +0.5. | 17 |
| 14 | Raw Room-Temperature Fatigue Life Data for Transverse Notched Annealed Ti-6Al-4V Sheet, R-ratio = +0.1. | 18 |
| 15 | Raw Room-Temperature Fatigue Life Data for Transverse Notched Annealed Ti-6Al-4V Sheet, R-ratio = -0.5. | 18 |
| 16 | Residual Surface Stress (KSI) vs. Fatigue Life of Selected Specimens. | 31 |

SECTION I

INTRODUCTION

The fatigue data published in MIL-HDBK-5 for annealed Ti-6Al-4V bar and extrusion prior to 1987 was based on material produced during the 1950's. It does not represent material produced using current production techniques. As a cooperative government-industry effort, three lots of annealed Ti-6Al-4V sheet material supplied by two manufacturers were tested to develop fatigue life curves for MIL-HDBK-5. Notched ($K_t=3.0$) and unnotched configurations of longitudinal and transverse specimens were tested at three different stress ratios. Although fatigue data are not considered as design allowables in MIL-HDBK-5, they are presented in the handbook as typical properties of a material.

The results of the fatigue testing were forwarded to the Battelle Memorial Institute, Columbus, Ohio, for analysis, reduction, and inclusion in MIL-HDBK-5.

SECTION II

MATERIALS AND SPECIMENS

Three lots of annealed Ti-6Al-4V sheet were supplied by two different manufacturers. The Titanium Metals Corporation of America, Toronto, Ohio, (Timet) supplied 0.070-inch sheet, while the RMI Company, Niles, Ohio supplied sheet in thicknesses of 0.063 inch and 0.078 inch. Material was manufactured to meet the requirements of MIL-T-9046H, Type III, Composition C. The RMI supplied material was production annealed at 1450°F for 15 minutes and air cooled; the Timet material was annealed for 30 minutes at 1400°F and air cooled.

Chemical compositions of each lot of material are presented in Table 1. Tensile properties are listed in Table 2.

Longitudinal and transverse notched and unnotched fatigue specimens were excised from each sheet of titanium as shown in Figures 1 and 2. Specimens were designed in accordance with ASTM Standard E466, "Constant Amplitude Axial Fatigue Tests of Metallic Materials." Notched specimens had a stress concentration factor (K_t) of 3, calculated using R.E. Peterson's Stress Concentration Design Factors (New York: John Wiley and Sons, Inc., 1953), p. 26.

Each notched specimen was inspected using an optical comparator to confirm that the notch root radius and depth were the specified dimensions to yield a K_t of 3. It was noted that the surface texture of the notch walls resembled the texture of

orange peels. This characteristic indicated that the notches had originally been cut on an electro-discharge machine (EDM). Since the surface heat affected zone (HAZ) caused by an EDM could affect fatigue crack initiation and consequently the fatigue life, the notches were remachined on a grinding wheel to remove 0.005 inch of material in the HAZ of each notch. The new notch dimensions were specified to maintain a K_t of 3, however.

All specimens were machined to a surface finish of 32 RMS or better; care was taken to keep the specimens and the raw sheet material free from scratches. The gage sections of all specimens were lightly polished with 400-grit emery paper to remove surface scratches. Notch roots were left in the as-machined condition.

Eighty-eight specimens, as noted in Tables 4 through 15, were polished with a high-speed buffing wheel. There was concern that surface work hardening due to the buffing would affect the fatigue life of the specimens. Of the 88, the visual effects of buffing were removed from the specimen edges only on 18 specimens by lightly sanding with 400-grit emery paper. For the remaining 70 specimens, the buffing effects were removed by sanding the entire gage section with 400-grit paper. See Tables 4 through 15.

Mr. M. R. Mitchell of the Rockwell International Corporation Science Center, Thousand Oaks, California, performed residual surface stress measurements on selected specimens. Stresses were measured on a PSD System using Cu radiation.

SECTION III

PROCEDURES

Constant-amplitude fatigue life curves were compiled for each lot of material at three different R-ratios (+0.5, +0.1, and -0.5) in both the longitudinal and transverse orientations. Maximum stress levels were chosen so that failure of the specimens would occur between 10^4 and 10^7 cycles in all cases. The test matrix is presented as Table 3.

Fatigue testing of all specimens run at positive R-ratios was conducted on a Rumul resonance-type fatigue machine at a frequency of 105 Hz. The Rumul proved unsuitable for the specimens tested at negative R-ratios, however. The combination of the relatively high maximum stresses with the compressive half-cycles caused the machine to behave in an unstable manner. The Rumul repeatedly triggered its limit switches during trial runs. Therefore, negative R-ratio tests were conducted on an MTS servohydraulic fatigue testing machine at 10-25 Hz.

During the negative R-ratio tests, two aluminum C-channel doublers were placed back-to-back to "sandwich" the specimens to prevent buckling. Teflon fabric was used to reduce friction between the specimen and the stiffening channels.

SECTION IV

RESULTS AND DISCUSSION

Raw fatigue data are presented in Tables 4 through 15. Those data were compiled into fatigue life curves (S-N curves) in Figures 3 through 14.

An attempt was made to compare the residual surface stresses measured by Rockwell International with the fatigue lives of certain specimens. Because of the limited number of replicate tests that were possible, however, a meaningful correlation could not be drawn. The listing of those residual stresses and the corresponding fatigue life data are presented in Table 16. It should be noted, however, that the residual stresses in any of the specimens were probably not high enough to affect specimen behavior.

The measurement of residual surface stresses will be included in a future MIL-HDBK-5 standard for analysis of fatigue data.

SECTION V

CONCLUSIONS

The inclusion of these data into MIL-HDBK-5 will add fatigue life curves for annealed Ti-6Al-4V sheet to the curves already in the handbook for solution treated and aged Ti-6Al-4V sheet.

The residual surface stresses were measured and recorded in an effort to correlate those stresses with specimen fatigue life. Although that correlation could not be made based on the limited specimens that had had residual surface stresses measured, the technique will be included in the future in a new MIL-HDBK-5 standard for analysis of fatigue data.

TABLE 1. CHEMICAL COMPOSITION OF T1-6Al-4V SHEET
DATA SUPPLIED BY MANUFACTURERS

| MANUFACTURER | SHEET THICKNESS, IN. | CHEMISTRY % | | | | | | | |
|--------------|----------------------|-------------|-------|------|-----|-----|--------|-------|-------|
| | | C | N | Fe | Al | V | Y | O | H |
| RMI | 0.063 | 0.02 | 0.011 | 0.17 | 6.0 | 3.9 | <50ppm | 0.137 | 61ppm |
| RMI | 0.078 | 0.02 | 0.014 | 0.16 | 6.2 | 4.0 | <50ppm | 0.148 | 57ppm |
| TIMET | 0.070 | 0.016 | 0.010 | 0.15 | 6.4 | 4.0 | <10ppm | 0.14 | 70ppm |

TABLE 2. TENSILE DATA OF ANNEALED T1-6Al-4V SHEET
DATA SUPPLIED BY MANUFACTURERS

| MANUFACTURER | THICKNESS (IN) | SPECIMEN ORIENTATION | YIELD STRENGTH (KSI) | ULTIMATE STRENGTH (KSI) | ELONGATION (%) |
|--------------|----------------|----------------------|----------------------|-------------------------|----------------|
| RMI | 0.063 | L | 140 | 149.4 | 11 |
| | | T | 142.9 | 151.8 | 12.5 |
| RMI | 0.078 | L | 146.1 | 150.3 | 10 |
| | | T | 136 | 145.1 | 13 |
| TIMET | 0.070 | L | 142 | 150 | 12 |
| | | T | 138 | 147 | 12 |

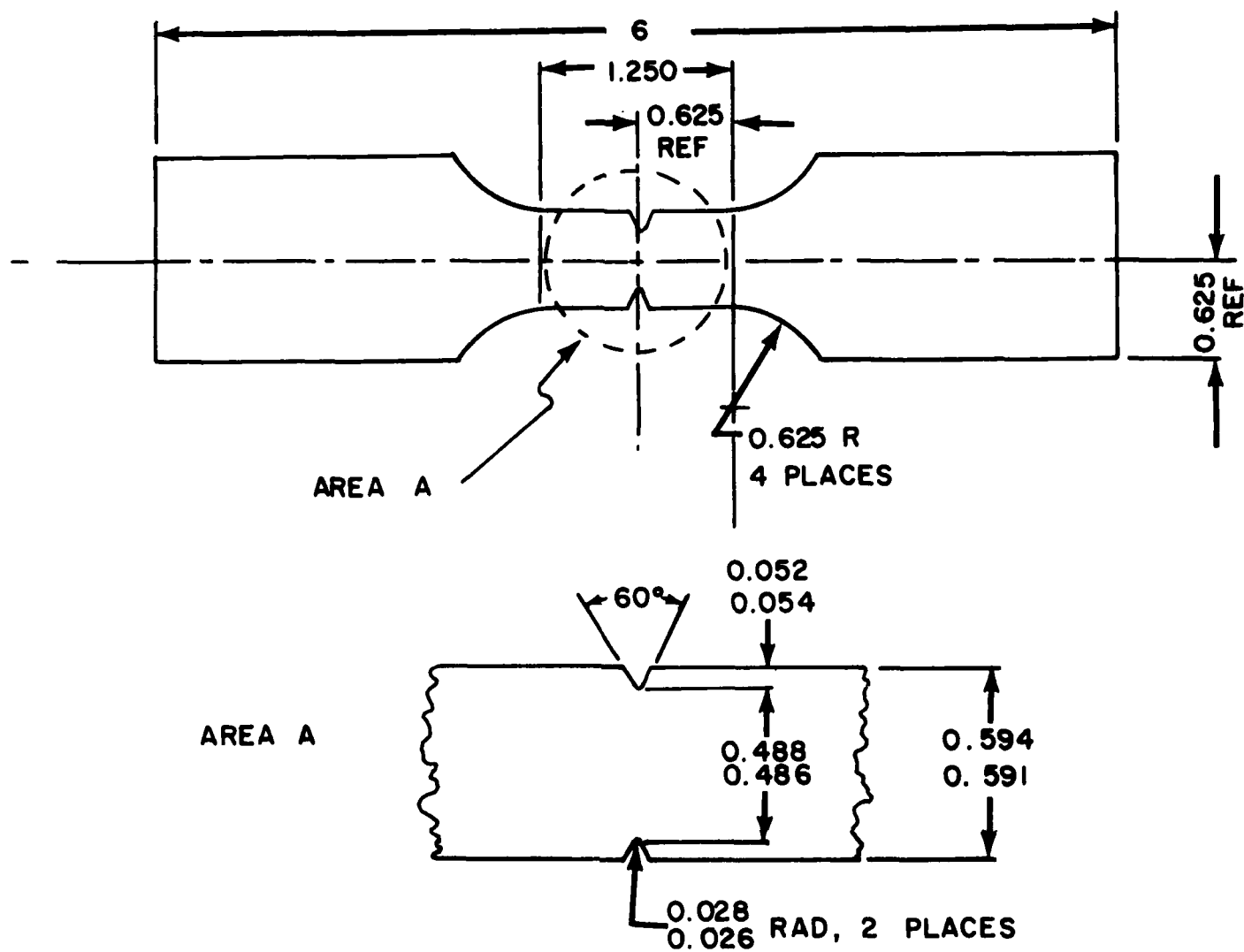


Figure 1. Notched Specimen Geometry.

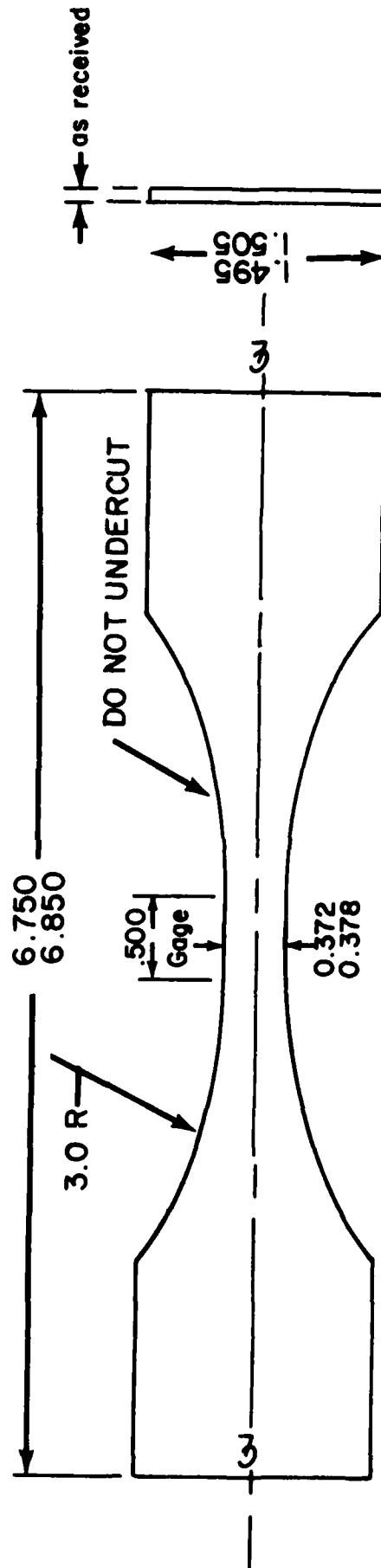


Figure 2. Unnotched Specimen Geometry.

TABLE 3 TEST MATRIX

| MFG: RMI | | | | | | | MFG TMCA | |
|------------------------|----------|--------|--------|--------|--------|--------|----------|--|
| STRESS RATIO (R) | HEAT A | | HEAT B | | HEAT C | | | |
| | LONGIT | TRANSV | LONGIT | TRANSV | LONGIT | TRANSV | | |
| | NOTCH UN | N U | N U | N U | N U | N U | | |
| | | | | | | | | |
| +0.5 | 15 15 | 5 5 | 5 5 | 5 5 | 15 15 | 6 6 | | |
| +0.1 | 15 15 | 5 5 | 5 5 | 5 5 | 15 15 | 6 6 | | |
| -0.5 | 15 15 | 5 5 | 5 5 | 5 5 | 15 15 | 6 6 | | |

TABLE 4. Raw Room-Temperature Fatigue Life Data for Longitudinal Unnotched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.5 at a Test Frequency of 105 Hz.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|--------------------------------|
| 16LU | 0.070 | 95 | 18093200 | RUNOUT; MB/ES (See Note Below) |
| 17LU | | 105 | 9635000 | RUNOUT; MB/ES |
| 18LU | | 110 | 9690700 | RUNOUT; MB/ES |
| 19LU | | 115 | 9066200 | MB/ES |
| 20LU | | 120 | 5833200 | MB/ES |
| 21LU | | 125 | 4846800 | MB/ES |
| 22LU | | 130 | 3091200 | MB/ES |
| 23LU | | 135 | 3023200 | MB/ES |
| 24LU | | 140 | 405600 | MB/ES |
| 25LU | | 140 | 134300 | MB/ES |
| 26LU | | 145 | 275400 | MB/ES |
| 27LU | | -- | -- | |
| 28LU | | 150 | 34120 | MB/ES |
| 29LU | | 155 | 14090 | MB/ES |
| 30LU | | 160 | -- | FAILED DURING LOADING; MB/ES |
| 16LUA | 0.078 | 125 | 8453100 | |
| 17LUA | | 120 | 11424100 | |
| 18LUA | | 120 | 3230000 | |
| 19LUA | | 120 | 7362800 | |
| 20LUA | | 110 | 16098800 | |
| 21LUA | | 130 | 3265900 | |
| 22LUA | | 130 | 5309600 | |
| 23LUA | | 135 | 2922900 | |
| 24LUA | | 135 | 3108100 | |
| 25LUA | | 140 | 2104100 | |
| 26LUA | | 140 | 3037400 | |
| 27LUA | | 145 | 342700 | |
| 28LUA | | 150 | 46800 | |
| 29LUA | | 150 | 97000 | |
| 30LUA | | 145 | 1768000 | |
| 6LUB | 0.063 | 148 | 25100 | |
| 7LUB | | 144 | 39800 | |
| 8LUB | | 158 | -- | FAILED DURING LOADING |
| 9LUB | | 156 | -- | " |
| 10LUB | | 152 | -- | " |

NOTE: MB/ES designates "Mechanically Buffed" specimens whose Edges were Sanded.

TABLE 5. Raw Room-Temperature Fatigue Life Data for Longitudinal Unnotched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.1 at a Test Frequency of 105 Hz.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|---------------------|
| 1LU | 0.070 | 140 | 27300 | MB (See Note Below) |
| 2LU | | 140 | 16300 | MB |
| 3LU | | 135 | 27100 | MB |
| 4LU | | 130 | 1906500 | MB |
| 5LU | | 130 | 906500 | MB |
| 6LU | | 125 | 1915200 | MB |
| 7LU | | 125 | 1695100 | MB |
| 8LU | | 120 | 83800 | MB |
| 9LU | | 120 | 1996400 | MB |
| 10LU | | 115 | 2874400 | MB |
| 11LU | | 132.5 | 34700 | MB |
| 12LU | | 131 | 35100 | MB |
| 13LU | | 131.5 | 910200 | MB |
| 14LU | | 131 | 140900 | MB |
| 15LU | | 143 | 7700 | MB |
| 1LUA | 0.078 | 100 | 4655250 | MISALIGNED |
| 2LUA | | 120 | 70600 | |
| 3LUA | | 90 | 24418700 | |
| 4LUA | | 110 | 150750 | |
| 5LUA | | 105 | 2332100 | |
| 6LUA | | 107.5 | 41800 | RUNOUT |
| 7LUA | | 102.5 | -- | |
| 8LUA | | 80 | 16353600 | |
| 9LUA | | 90 | 36881000 | |
| 10LUA | | 100 | 10005600 | |
| 11LUA | | 102.5 | 11215000 | RUNOUT |
| 12LUA | | 105 | 10430000 | |
| 13LUA | | 120 | 2975000 | |
| 14LUA | | 115 | 5613000 | |
| 15LUA | | 117.5 | 7584300 | |
| 1LUB | 0.063 | 135 | 26800 | |
| 2LUB | | 110 | 10510000 | |
| 3LUB | | 112.5 | 4785200 | |
| 4LUB | | 120 | 216500 | |
| 5LUB | | 130 | -- | |

NOTE: "MB" designates "Mechanically Buffed" specimens which were then sanded lightly overall with 400 grit sand paper.

TABLE 6. Raw Room-Temperature Fatigue Life Data for Longitudinal Unnotched Annealed Ti-6Al-4V Sheet. R-Ratio is -0.5 at a Test Frequency of 20 Hz, except as noted.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|---------------------------|
| 31LU | 0.070 | 125 | 6900 | MB/ES (See Note 1) |
| 32LU | | 120 | 23400 | MB/ES |
| 33LU | | 115 | 29700 | MB/ES |
| 34LU | | 110 | 27900 | MB/ES |
| 35LU | | 105 | -- | MB/ES |
| 36LU | | 98 | 41600 | 10Hz; MB (See Note Below) |
| 37LU | | 97.5 | 59800 | 10Hz; MB |
| 38LU | | 95 | 3407400 | 10Hz; MB |
| 39LU | | 95 | 4500100 | 10Hz |
| 40LU | | 92.5 | 6618900 | 10Hz |
| 41LU | | 95 | 54500 | 10Hz |
| 42LU | | 100 | 17700 | |
| 43LU | | 100 | 73700 | |
| 44LU | | 90 | 2546200 | 10Hz |
| 45LU | | 95 | -- | 10Hz |
| 46LU | | 97 | 71900 | 10Hz |
| 31LUA | 0.078 | 80 | 1194300 | 105Hz |
| 32LUA | | 75 | -- | |
| 33LUA | | 70 | 2205700 | 105Hz |
| 34LUA | | 75 | 14665800 | RUNOUT, 25Hz |
| 35LUA | | -- | -- | |
| 36LUA | | 85 | 10075800 | RUNOUT, 25Hz |
| 37LUA | | 125 | 15900 | |
| 38LUA | | 115 | 34000 | 25Hz |
| 39LUA | | 100 | 45400 | 25Hz |
| 40LUA | | 90 | 2004300 | |
| 41LUA | | 95 | 1127300 | 25Hz |
| 42LUA | | 105 | 24000 | |
| 43LUA | | 120 | 15000 | |
| 44LUA | | 110 | 17200 | |
| 45LUA | | 95 | 78600 | |
| 11LUB | 0.063 | 90 | 10319200 | RUNOUT |
| 12LUB | | 105 | 45700 | |
| 13LUB | | 100 | 482900 | |
| 14LUB | | 120 | -- | BROKE DURING LOADING |
| 15LUB | | 115 | 35600 | |

NOTE: "MB/ES" designates "Mechanically Buffed" specimens whose Edges were Sanded.
"MB" designates mechanically buffed specimens that were lightly sanded overall with 400-grit sandpaper.

TABLE 7. Raw Room-Temperature Fatigue Life Data for Transverse Unnotched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.5.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|---------------------------|
| 7TU | 0.070 | 136 | 230400 | 10Hz; MB (See Note Below) |
| 8TU | | 144 | 52500 | 10Hz; MB |
| 9TU | | 134 | 355500 | 10Hz; MB |
| 10TU | | 146 | 44000 | 10Hz; MB |
| 11TU | | 128 | 1741200 | 20Hz; MB |
| 12TU | | 126 | 1499100 | 20Hz; MB |
| 6TUA | 0.078 | 126 | -- | HYDRAULIC MACHINE FAILURE |
| 7TUA | | 120 | 10000000 | RUNOUT, 20Hz |
| 8TUA | | 140 | 56500 | 10Hz |
| 9TUA | | 130 | 3330000 | 10Hz |
| 10TUA | | 150 | 200 | 10Hz |
| 6TUB | 0.063 | 124 | -- | HYDRAULIC MACHINE FAILURE |
| 7TUB | | 142 | 56300 | 15Hz |
| 8TUB | | 132 | 3880200 | 20Hz |
| 9TUB | | 138 | 114600 | 15Hz |
| 10TUB | | 133 | 257000 | 15Hz |

NOTE: "MB" designates "Mechanically Buffed" specimens which were then sanded lightly overall with 400-grit sandpaper.

TABLE 8. Raw Room-Temperature Fatigue Life Data for Transverse Unnotched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.1 at a Test Frequency of 15 Hz, except as noted.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|----------|
| 1TU | 0.070 | 115 | 920700 | 10HZ |
| 2TU | | 135 | 31300 | |
| 3TU | | 112 | 18500 | |
| 4TU | | 108 | 1372600 | |
| 5TU | | 118 | 899200 | |
| 6TU | | 126 | 73000 | |
| 1TUA | 0.078 | 90 | 10000000 | RUNOUT |
| 2TUA | | 110 | 143000 | |
| 3TUA | | 110 | 34500 | |
| 4TUA | | 100 | 3452700 | |
| 5TUA | | 105 | 8506400 | |
| 1TUB | 0.063 | 139 | 10500 | |
| 2TUB | | 124 | 787300 | |
| 3TUB | | 105 | 3320700 | |
| 4TUB | | 120 | 1224000 | |
| 5TUB | | 130 | 45000 | |

TABLE 9. Raw Room-Temperature Fatigue Life Data for Transverse Unnotched Annealed Ti-6Al-4V Sheet. R-Ratio is -0.5 at a Test Frequency of 20 Hz, except as noted.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|----------|
| 13TU | 0.070 | 90 | 2410400 | 10HZ |
| 14TU | | 85 | 6615500 | |
| 15TU | | 100 | 2225900 | |
| 16TU | | 115 | 24000 | |
| 17TU | | 95 | 1592500 | |
| 18TU | | 105 | 37400 | |
| 19TU | | 97.5 | 61100 | |
| 20TU | | 102.5 | 30800 | |
| 11TUA | 0.078 | 110 | 49200 | |
| 12TUA | | 95 | 5002000 | |
| 13TUA | | 102.5 | 430900 | |
| 14TUA | | 90 | 5426000 | |
| 15TUA | | 120 | 37000 | |
| 11TUB | 0.063 | 100 | 43400 | |
| 12TUB | | 95 | 1052300 | |
| 13TUB | | 97.5 | 1948600 | |
| 14TUB | | 105 | 35500 | |
| 15TUB | | 97.5 | 49000 | |

TABLE 10. Raw Room-Temperature Fatigue Life Data for Longitudinal Notched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.5 at a Test Frequency of 95 Hz.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|----------------------|
| 31LN | 0.070 | -- | -- | |
| 32LN | | 58 | 762300 | MB (See Note) |
| 33LN | | 66 | 904100 | MB |
| 34LN | | 84 | 49000 | MB |
| 35LN | | 68 | 102000 | MB |
| 36LN | | 62 | 1478600 | MB |
| 37LN | | 60 | -- | MB |
| 38LN | | 72 | 70500 | MB |
| 39LN | | 50 | 3625800 | MB |
| 40LN | | 52 | 3805800 | MB |
| 41LN | | 56 | 2080500 | MB |
| 42LN | | 80 | 56400 | MB |
| 43LN | | 64 | 67200 | MB |
| 44LN | | 70 | 92700 | MB |
| 45LN | | 60 | 902600 | MB |
| 16LNA | 0.078 | 90 | -- | BROKE DURING LOADING |
| 17LNA | | 60 | 35900 | |
| 18LNA | | 30 | 297300 | |
| 19LNA | | 10 | 33648800 | RUNOUT |
| 20LNA | | 20 | 1144100 | |
| 21LNA | | 15 | 18365000 | |
| 22LNA | | 20 | 16045200 | RUNOUT |
| 23LNA | | 25 | 623200 | |
| 24LNA | | 68 | 137200 | |
| 25LNA | | 62 | 1358700 | |
| 26LNA | | 64 | 2387100 | |
| 27LNA | | 54 | 4819400 | |
| 28LNA | | 78 | 40900 | |
| 29LNA | | 66 | 169800 | |
| 30LNA | | 46 | 8780000 | |
| 11LNB | 0.063 | 64 | 3464400 | |
| 12LNB | | 74 | 79900 | |
| 13LNB | | 70 | 181700 | |
| 14LNB | | 60 | 4452200 | |
| 15LNB | | 66 | 4603500 | |

NOTE: "MB" designates Mechanically Buffed specimens that were lightly sanded overall with 400-grit sandpaper.

TABLE 11. Raw Room-Temperature Fatigue Life Data for Longitudinal Notched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.1 at a Test Frequency of 95 Hz, except as noted.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|---------------------------|
| 1LN | 0.070 | 40 | 1729900 | 20Hz; MB (See Note Below) |
| 2LN | | 46 | 826100 | MB |
| 3LN | | 50 | 38400 | 20Hz; MB |
| 4LN | | 52 | 1240700 | MB |
| 5LN | | 35 | 5311700 | 20Hz; MB |
| 6LN | | 50 | 57500 | MB |
| 7LN | | 45 | 1160000 | 20Hz; MB |
| 8LN | | 44 | 1642600 | MB |
| 9LN | | 55 | 43300 | 25Hz; MB |
| 10LN | | 48 | 612800 | MB |
| 11LN | | 58 | 48200 | 10Hz; MB |
| 12LN | | 62 | 28600 | MB |
| 13LN | | 60 | 35600 | 10Hz; MB |
| 14LN | | 38 | 1784300 | MB |
| 15LN | | 48 | 1133100 | 20Hz; MB |
| 1LNA | 0.078 | 46 | 2638500 | |
| 2LNA | | 54 | 82600 | |
| 3LNA | | 50 | 5353200 | |
| 4LNA | | 62 | 48500 | |
| 5LNA | | 52 | 47800 | 20Hz |
| 6LNA | | 50 | 59500 | |
| 7LNA | | 50 | 537400 | 20Hz |
| 8LNA | | 64 | 28200 | |
| 9LNA | | 48 | 22700 | |
| 10LNA | | 52 | 753400 | |
| 11LNA | | 48 | 832400 | |
| 12LNA | | 54 | 106300 | |
| 13LNA | | 42 | 1593500 | |
| 14LNA | | 50 | 1412300 | |
| 15LNA | | 56 | 112900 | |
| 1LNB | 0.063 | 50 | 1354600 | |
| 2LNB | | 46 | 2404300 | |
| 3LNB | | 52 | 1153800 | |
| 4LNB | | 36 | 3980800 | |
| 5LNB | | 58 | 77800 | |

NOTE: "MB" designates Mechanically Buffed specimens that were lightly sanded overall with 400-grit sandpaper.

TABLE 12. Raw Room-Temperature Fatigue Life Data for Longitudinal Notched Annealed Ti-6Al-4V Sheet. R-Ratio is -0.5 at a Test Frequency of 20 Hz.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|---------------------|
| 16LN | 0.070 | 28 | 2097500 | MB (See Note Below) |
| 17LN | | 42 | 40700 | MB |
| 18LN | | 34 | 3031700 | MB |
| 19LN | | 40 | 67100 | MB |
| 20LN | | 38 | 1457400 | MB |
| 21LN | | 46 | 33800 | MB |
| 22LN | | 24 | 10666900 | MB |
| 23LN | | 36 | 109000 | MB |
| 24LN | | 40 | 996500 | MB |
| 25LN | | 42 | 80700 | MB |
| 26LN | | 44 | 807500 | MB |
| 27LN | | 26 | 8860500 | MB |
| 28LN | | 32 | 1713800 | MB |
| 29LN | | 50 | 15800 | MB |
| 30LN | | 48 | 20800 | MB |
| 31LN | | 30 | 4623800 | MB |
| 31LNA | 0.078 | 20 | 3612500 | RUNOUT |
| 32LNA | | 15 | 10000000 | |
| 33LNA | | 30 | 81800 | |
| 34LNA | | 22 | 8462600 | |
| 35LNA | | 42 | 1374200 | |
| 36LNA | | 48 | 13900 | |
| 37LNA | | 38 | 440000 | |
| 38LNA | | 34 | 786900 | |
| 39LNA | | 36 | 59600 | |
| 40LNA | | 40 | 1357600 | |
| 41LNA | | 46 | 33900 | RUNOUT |
| 42LNA | | 26 | 5919100 | |
| 43LNA | | 28 | 10000000 | |
| 44LNA | | 32 | 2452100 | |
| 45LNA | | 46 | 10200 | |
| 7LNB | 0.063 | 50 | 1554600 | |
| 8LNB | | 46 | 2404300 | |
| 9LNB | | 52 | 1153800 | |
| 10LNB | | 36 | 3980800 | |

NOTE: "MB" designates Mechanically Buffed specimens that were lightly sanded overall with 400-grit sandpaper.

TABLE 13. Raw Room-Temperature Fatigue Life Data for Transverse Notched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.5 at a Test Frequency of 95 Hz.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|----------|
| 7TN | 0.070 | 62 | 942400 | 10HZ |
| 8TN | | 60 | 892300 | |
| 9TN | | 64 | 631600 | |
| 10TN | | 66 | 181300 | |
| 11TN | | 58 | 616600 | |
| 12TN | | 68 | 89500 | |
| 13TN | | 55 | 1587900 | |
| 11TNA | 0.078 | 65 | 78300 | |
| 14TNA | | 55 | 4492300 | |
| 15TNA | | 45 | 25583400 | |
| 11TNB | 0.063 | 52 | 12123400 | |
| 12TNB | | 58 | 3141500 | |
| 13TNB | | 70 | 71700 | |
| 14TNB | | 60 | 175400 | |
| 15TNB | | 80 | 40500 | |

TABLE 14. Raw Room-Temperature Fatigue Life Data for Transverse Notched Annealed Ti-6Al-4V Sheet. R-Ratio is +0.1 at a Test Frequency of 95 Hz, except as noted.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|----------|
| 1TN | 0.070 | 100 | 2400 | 20HZ |
| 2TN | | 85 | 6700 | 20HZ |
| 3TN | | 70 | 8700 | 20HZ |
| 4TN | | 60 | 41300 | 20HZ |
| 5TN | | 50 | 438500 | 20HZ |
| 6TN | | 40 | 1560700 | 20HZ |
| 1TNA | 0.078 | 48 | 1888300 | |
| 2TNA | | 50 | 1929400 | |
| 3TNA | | 56 | 48300 | |
| 4TNA | | 52 | 1444000 | |
| 5TNA | | 36 | 4743000 | |
| 1TNB | 0.063 | 50 | 2032700 | |
| 2TNB | | 32 | 10000000 | RUNOUT |
| 3TNB | | 54 | 63200 | |
| 4TNB | | 44 | 2009700 | |
| 5TNB | | 54 | 41700 | |

TABLE 15. Raw Room-Temperature Fatigue Life Data for Transverse Notched Annealed Ti-6Al-4V Sheet. R-Ratio is -0.5 at a Test Frequency of 20 Hz.

| Specimen ID | Sheet Thickness (in) | Maximum Stress (KSI) | Cycles to Failure | Comments |
|-------------|----------------------|----------------------|-------------------|----------|
| 14TN | 0.070 | 46 | 34100 | |
| 15TN | | 34 | 812300 | |
| 16TN | | 26 | 2390600 | |
| 17TN | | 36 | 1824600 | |
| 18TN | | 32 | 860900 | |
| 19TN | | 38 | 593900 | |
| 20TN | | 22 | 10378900 | |
| 6TNA | 0.078 | 52 | 8900 | |
| 8TNA | | 18 | 5415800 | |
| 9TNA | | 30 | 2212500 | |
| 10TNA | | 40 | 64200 | |
| 6TNB | 0.063 | 50 | 25300 | |
| 7TNB | | 30 | 103000 | |
| 8TNB | | 34 | 417400 | |
| 9TNB | | 24 | 10200000 | |
| 10TNB | | 28 | 3998300 | |

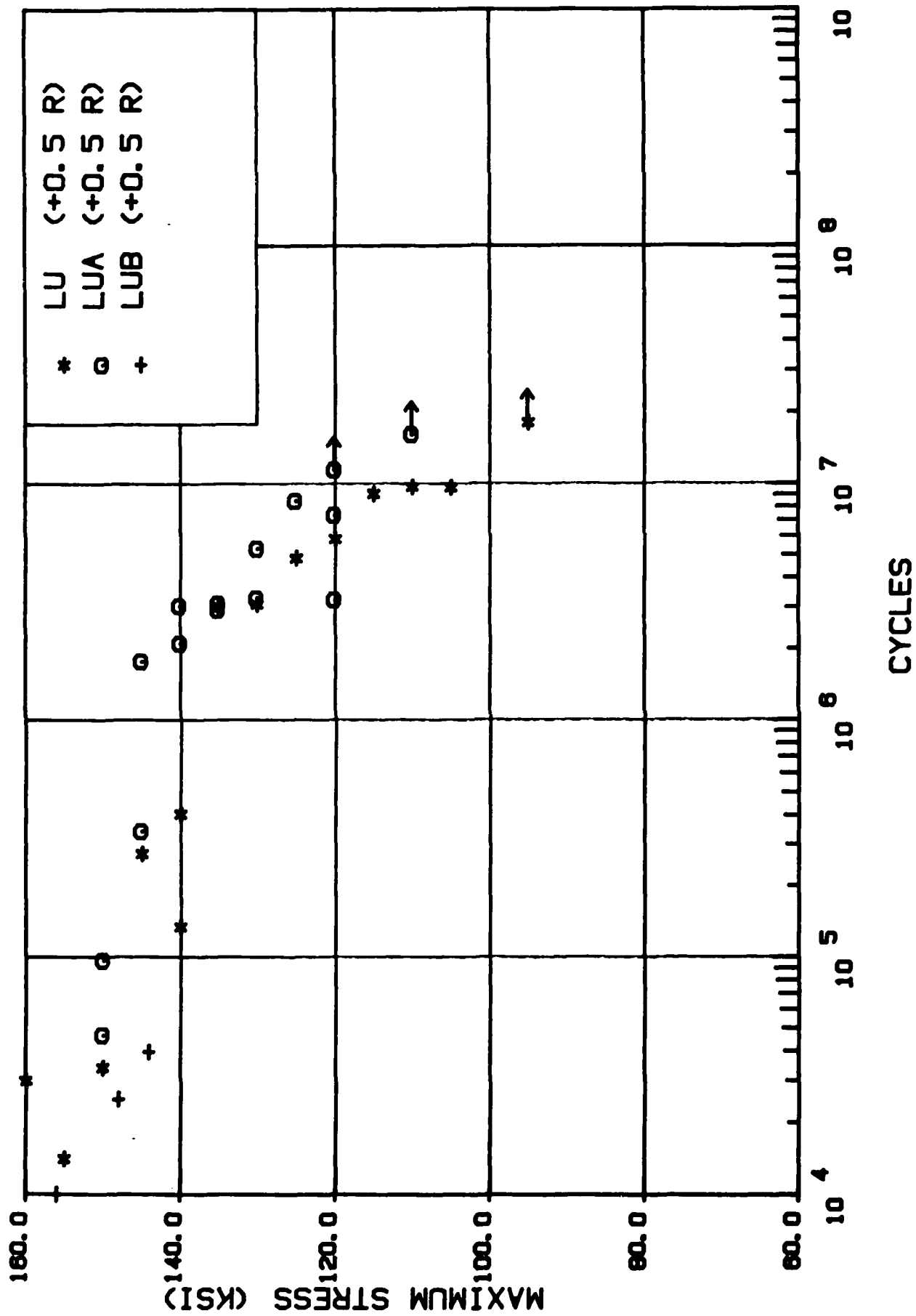


Figure 3. S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-Ratio = +0.5.

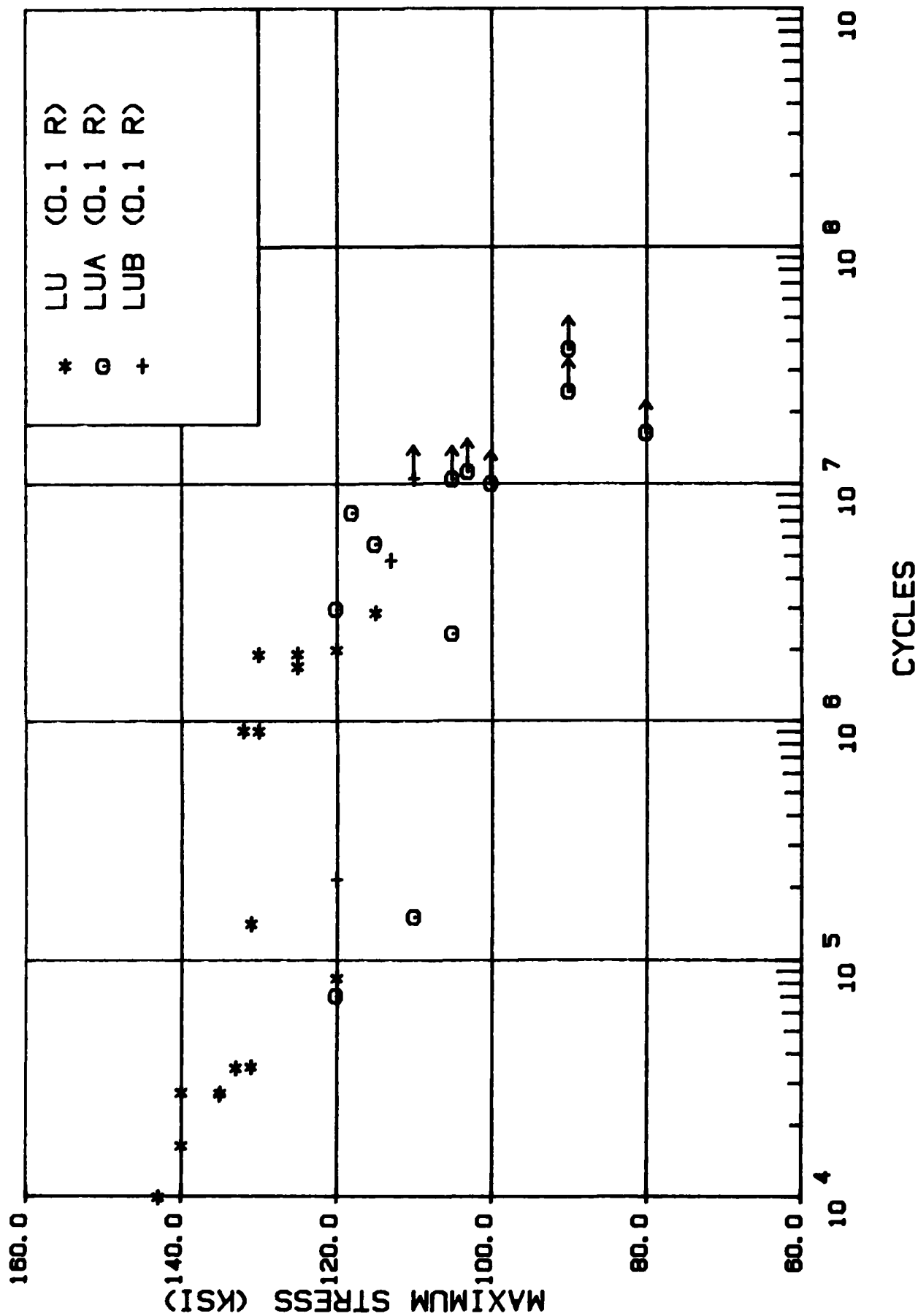
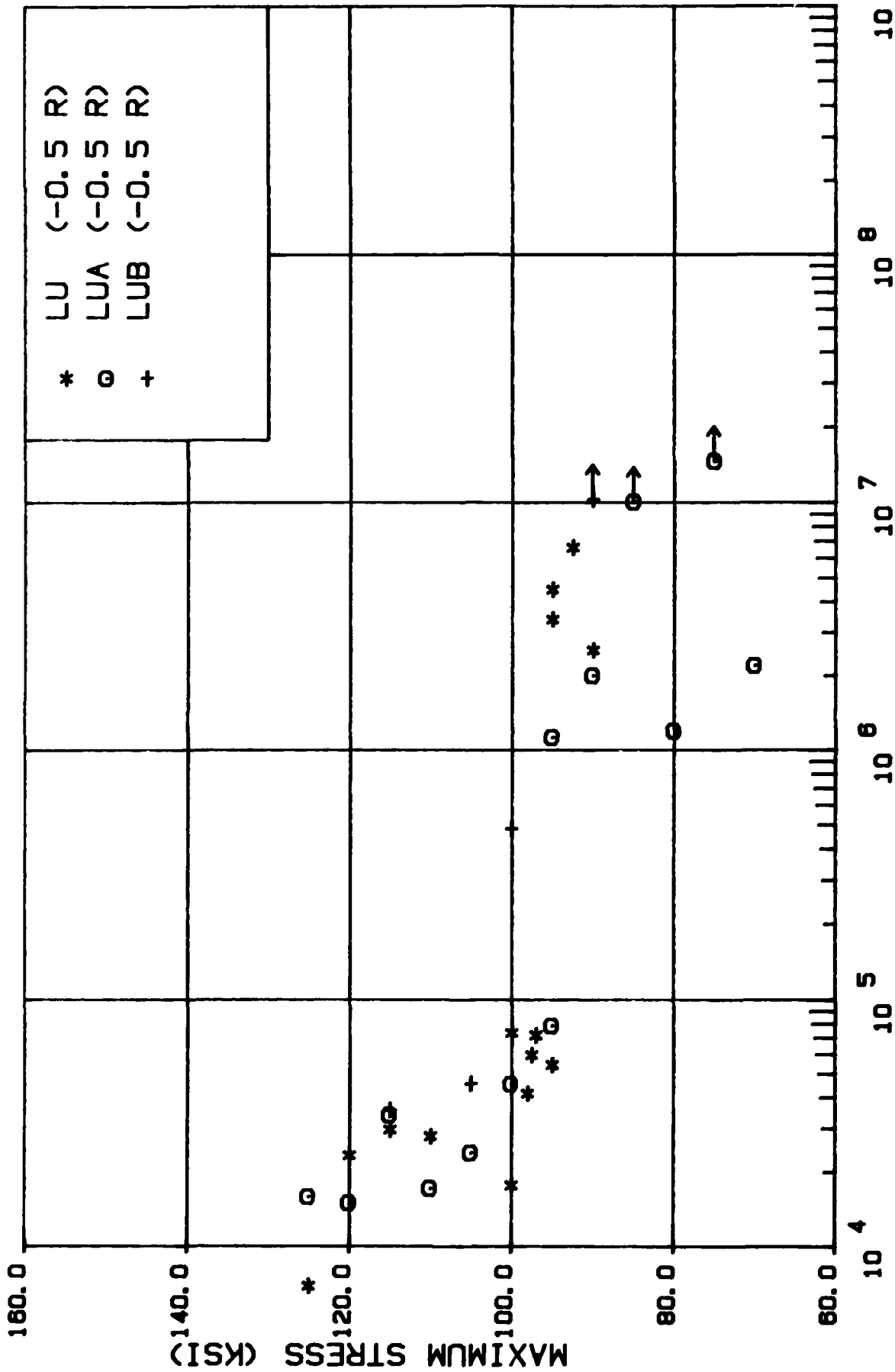


Figure 4. S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-Ratio = +0.1.



CYCLES

Figure 5. S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-Ratio = -0.5.

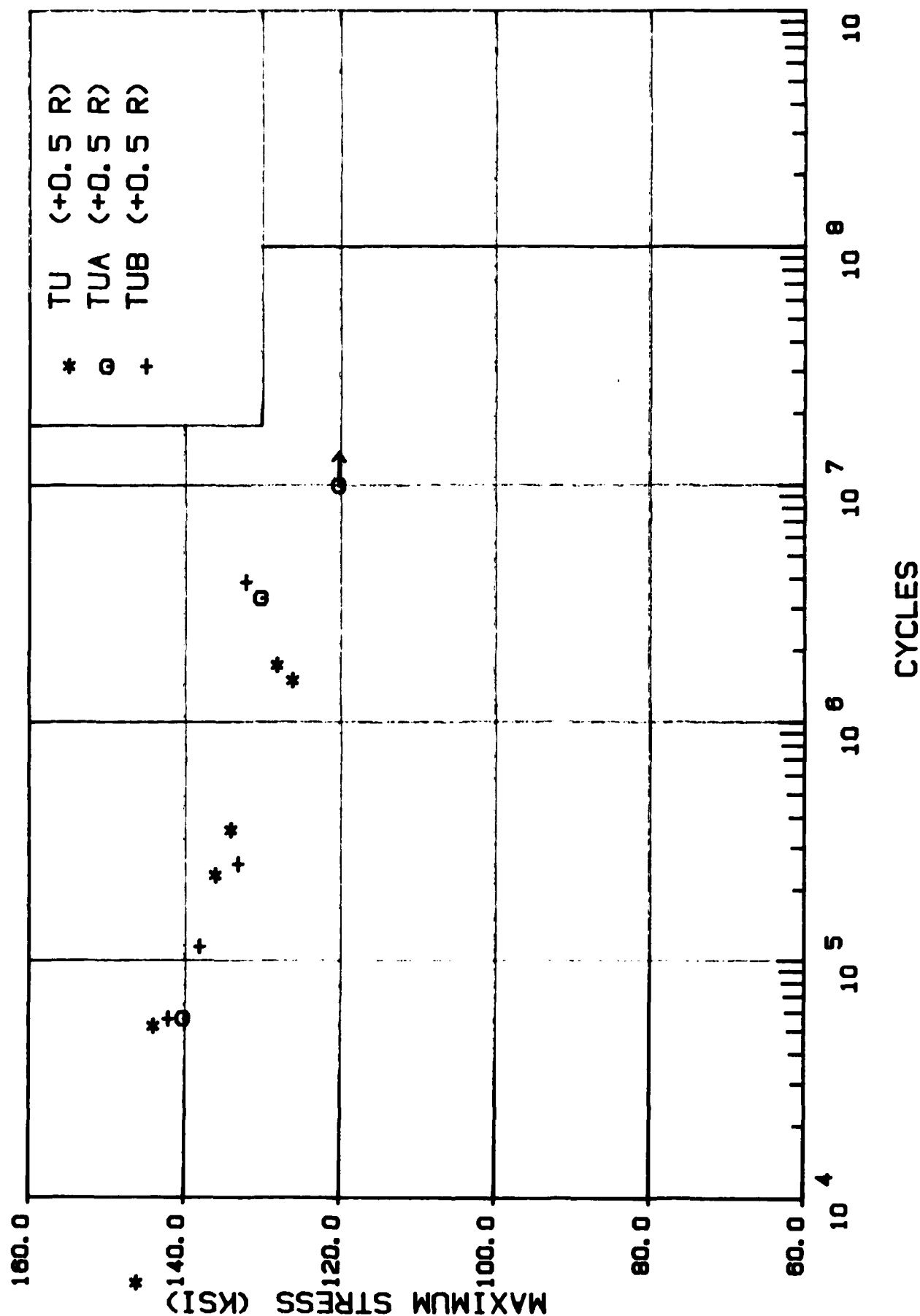


Figure 6. S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-Ratio = +0.5.

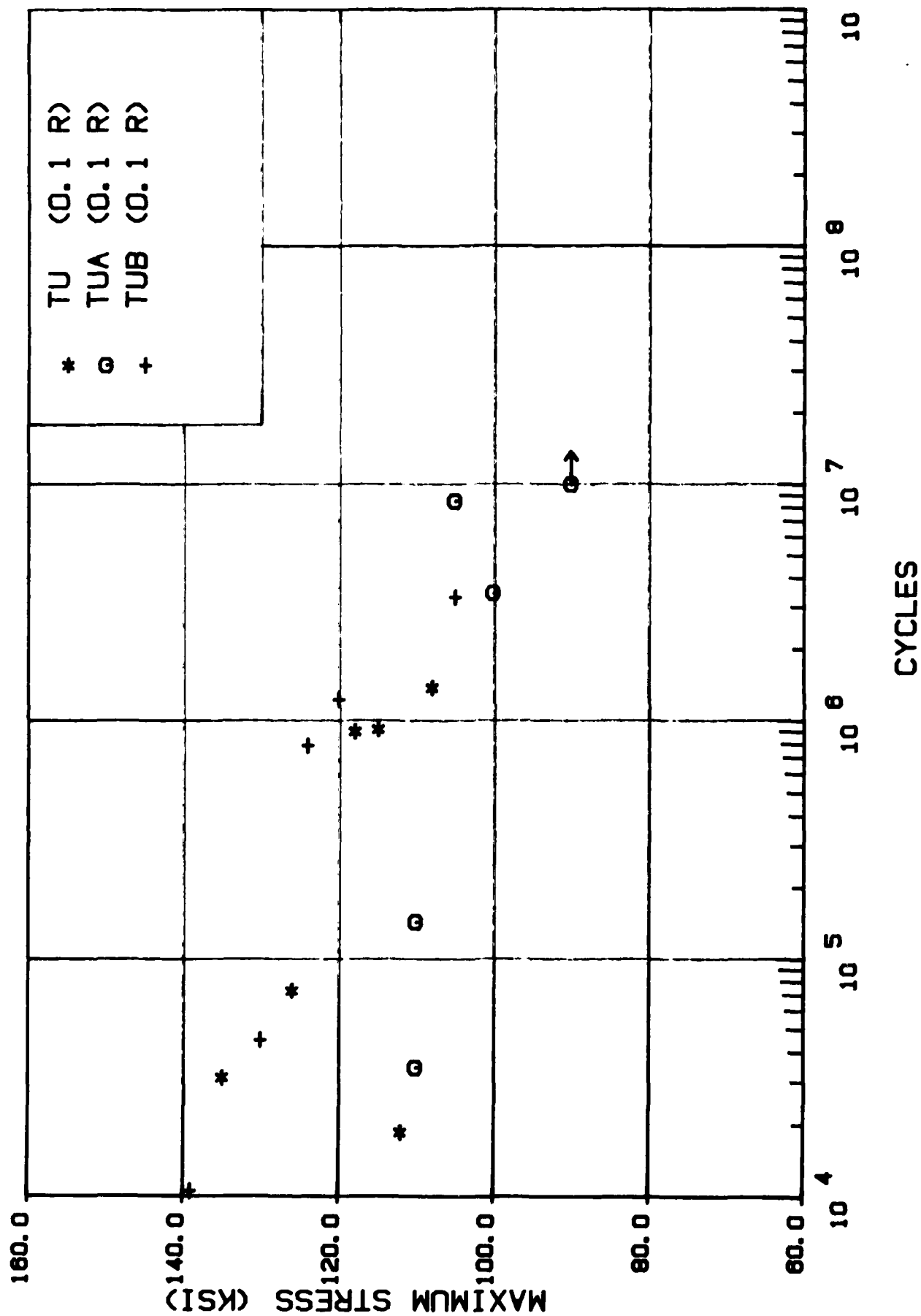


Figure 7. S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-Ratio = +0.1.

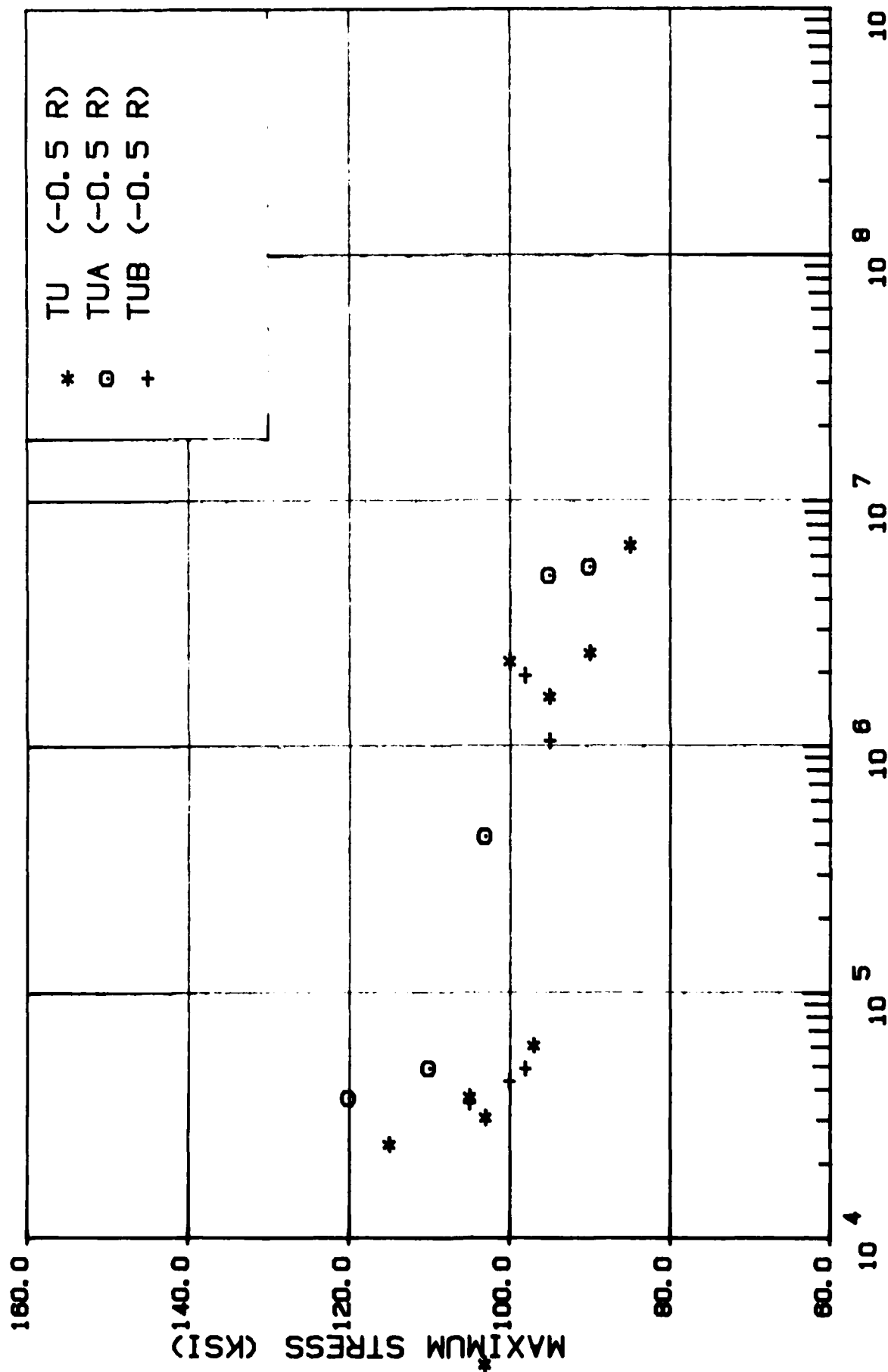


Figure 8. S-N Plot for Unnotched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-Ratio = -0.5.

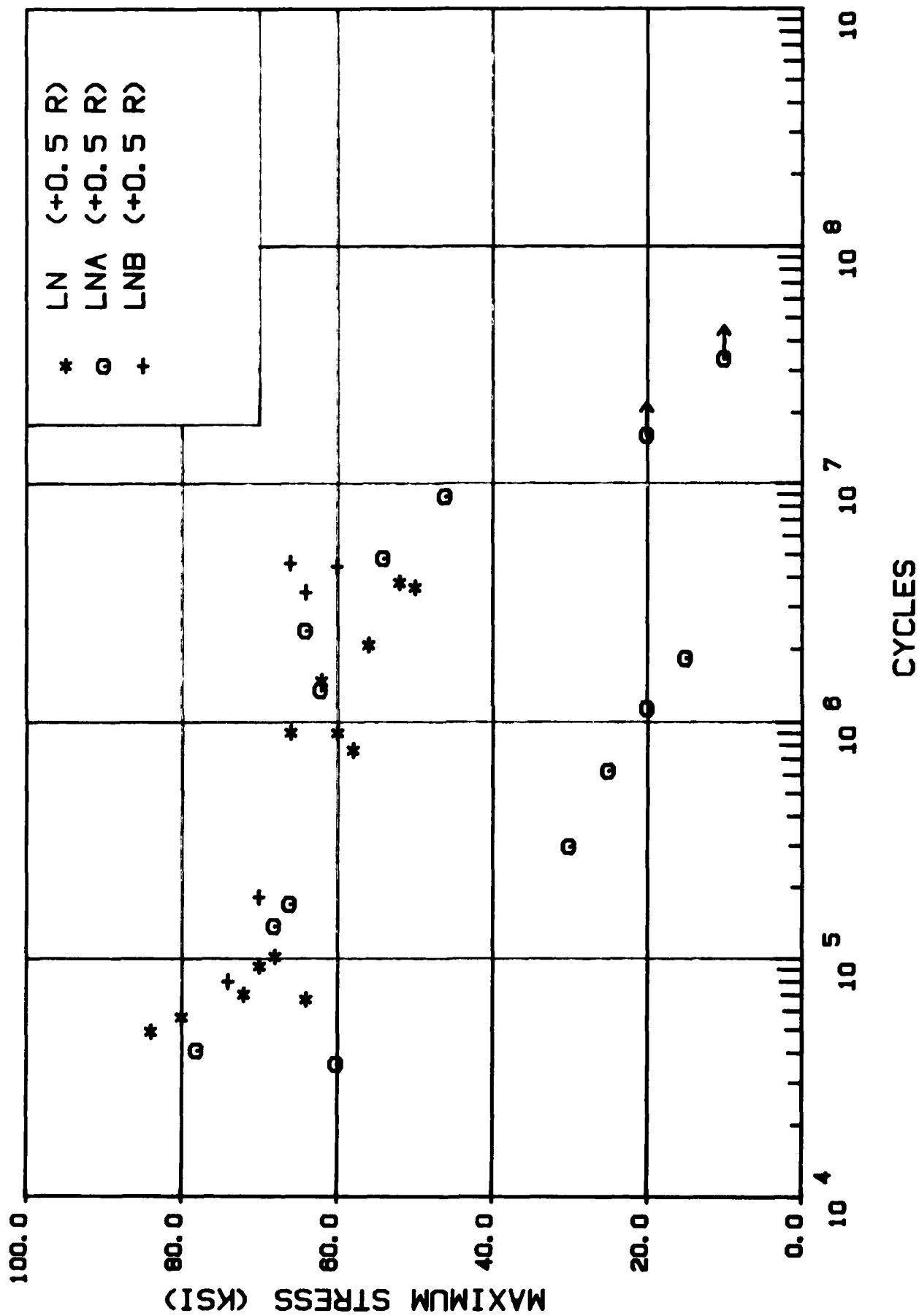


Figure 9. S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-Ratio = +0.5.

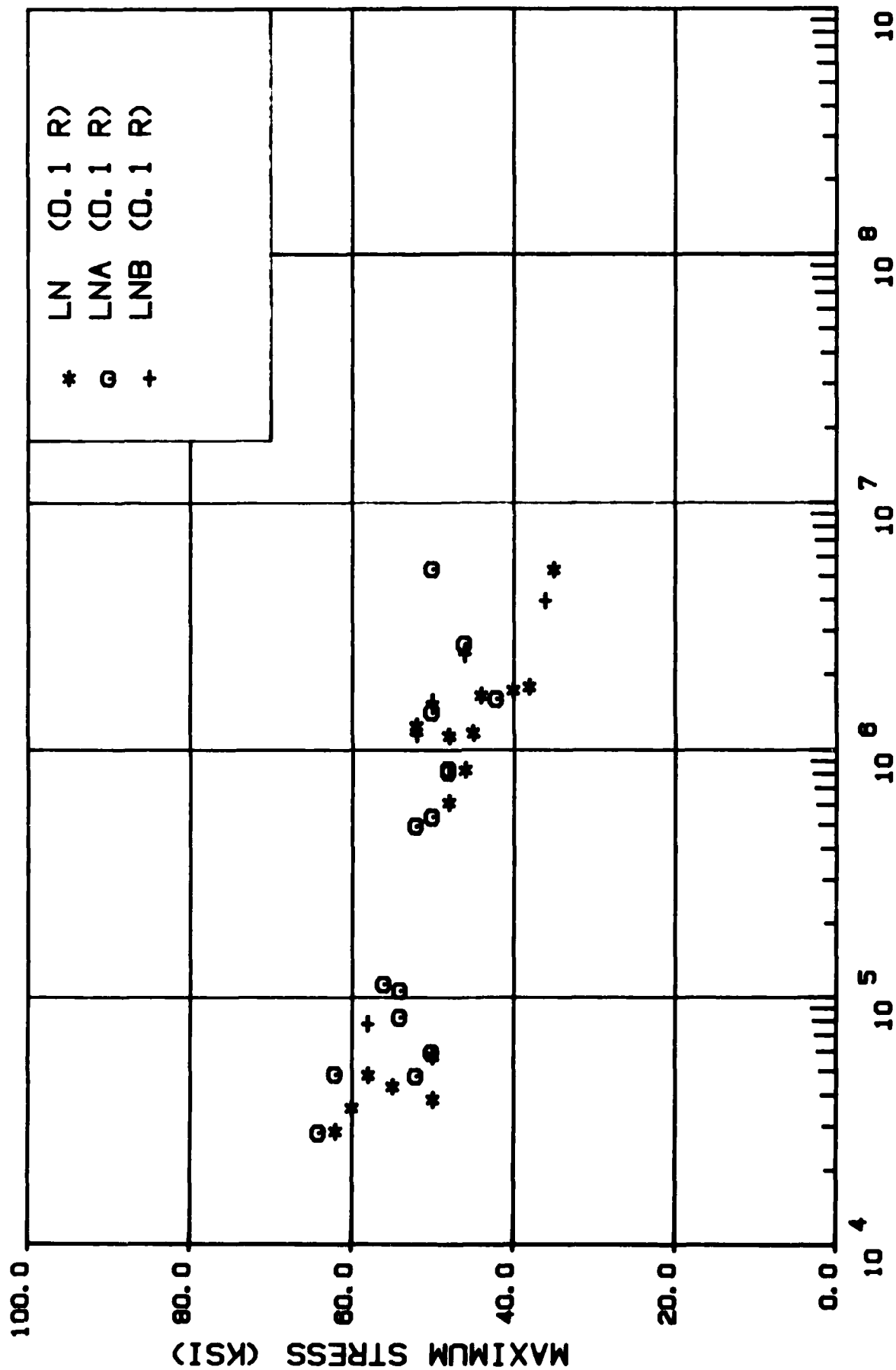


Figure 10. S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-Ratio = +0.1.

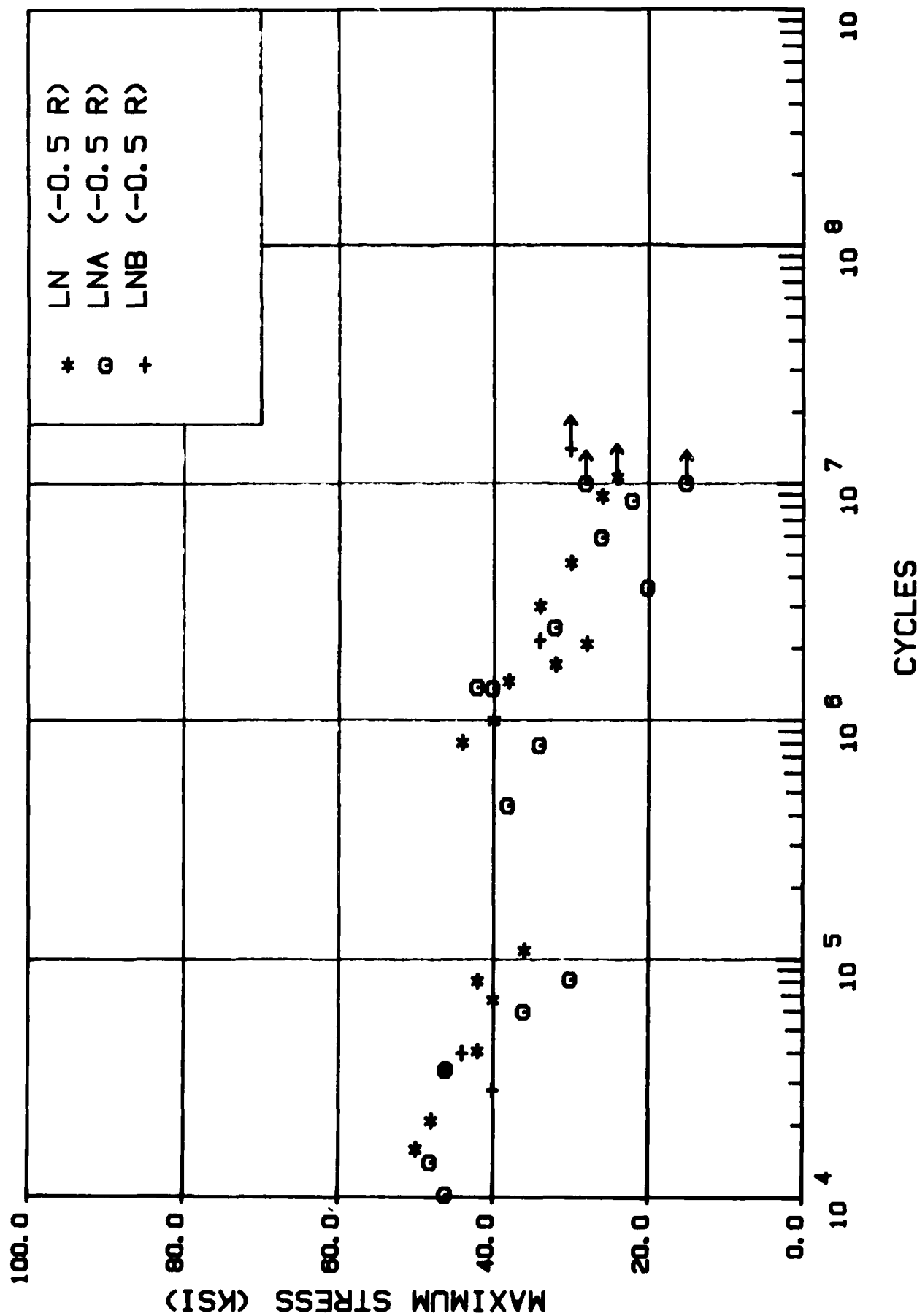


Figure 11. S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Longitudinal Orientation, R-Ratio = -0.5.

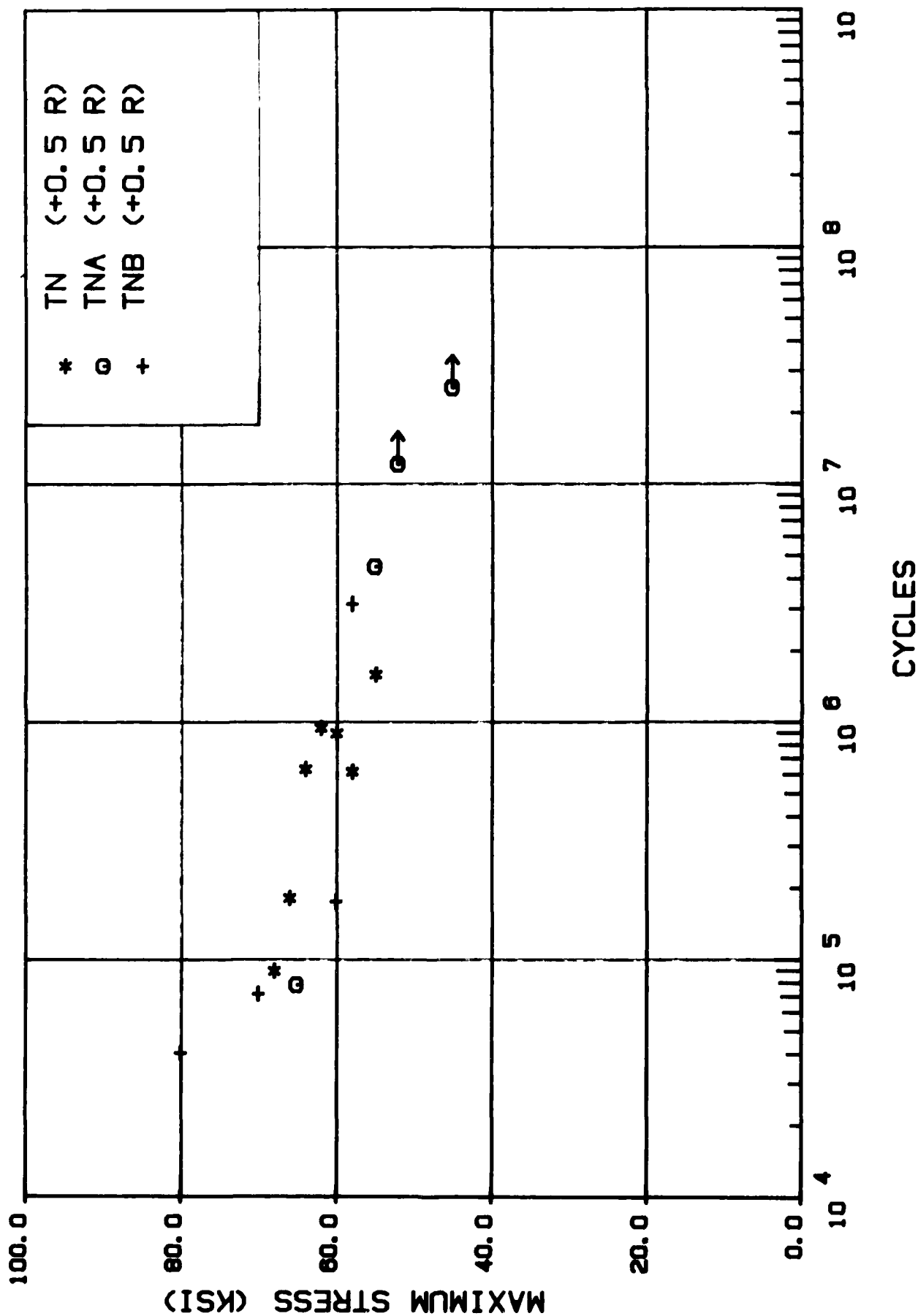


Figure 12. S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-Ratio = +0.5.

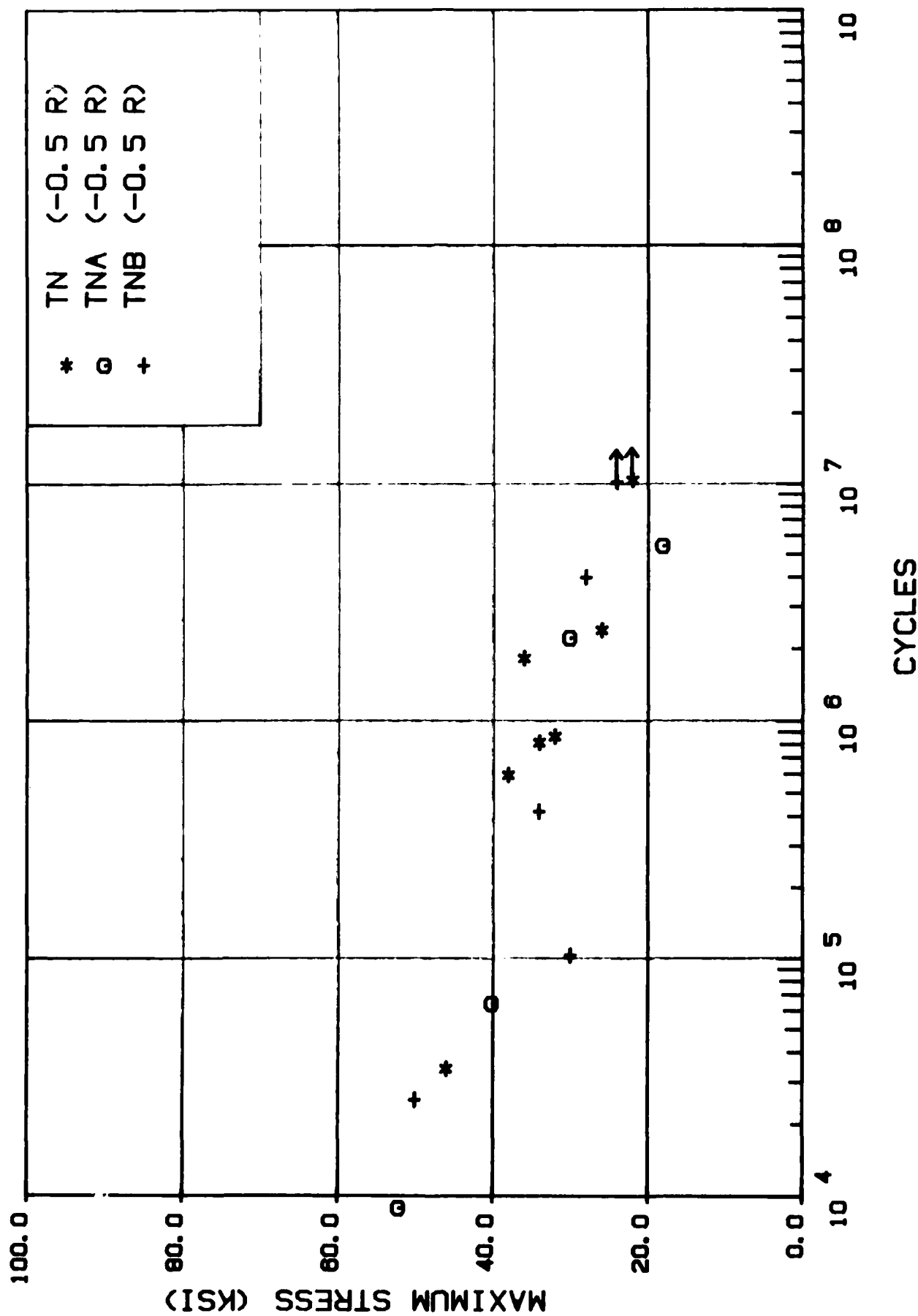


Figure 14. S-N Plot for Notched, Annealed Ti-6Al-4V Sheet at Room Temperature, Transverse Orientation, R-Ratio = -0.5.

TABLE 16 . RESIDUAL SURFACE STRESS IN ksi
vs. FATIGUE LIFE OF SELECTED SPECIMENS

| SPEC. NO. | POS 1 | POS 2 | POS 3 | GRIP A | GRIP B | R RATIO | MAX STRESS | CYCLES TO FAILURE |
|-----------|-------|-------|-------|--------|--------|---------|------------|-------------------|
| 44LNA | -7 | -35 | -5 | -- | -- | -0.5 | 32 | 2,452,100 |
| 45LNA | -1 | -10 | -7 | -- | -- | -0.5 | 46 | 10,200 |
| 14TNA | -6 | -51 | -3 | -- | -- | +0.5 | 55 | 4,492,300 |
| 15TNA | -6 | -73* | -13 | -- | -- | +0.5 | 45 | 25,583,400 |
| 14LNB | 0 | -5 | -5 | -- | -- | +0.5 | 60 | 4,452,200 |
| 15LNB | -7 | -12 | -12 | -- | -- | +0.5 | 66 | 4,603,500 |
| 11TNB | -13 | -8 | -12 | -- | -- | +0.5 | 52 | 12,123,400 |
| 12TNB | -6 | -3 | -7 | -- | -- | +0.5 | 58 | 3,141,500 |
| 30LN | -5 | -3 | +1 | +1 | -12 | -0.5 | 48 | 20,800 |
| 31LN | -6 | -9 | -7 | +3 | +2 | -0.5 | 30 | 4,623,800 |
| 13TN | -20 | -23* | -27* | +1 | +1 | +0.5 | 55 | 1,587,900 |
| 14TN | -7* | -22 | -11 | -1 | +2 | -0.5 | 46 | 34,100 |

*AVERAGE OF TWO MEASUREMENTS

*PSD SYSTEM, Cu RADIATION

